SIMULATION OF FOREST INSECT PEST MANAGEMENT

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INTRODUCTION

Interaction with a computer in a time-sharing environment permits the user to perform calculations in a variety of unique ways. Among these are simulations of the dynamic behavior of systems of concern to the user, together with the opportunity to perform control or regulatory actions during the simulation. In jargon, the user is permitted to play "what if?" This capability permits experimentation with a numerical representation of a real system rather than with the system itself. As a result, experiments can be conducted on the computer which would be impossibly expensive with the real system, or take generations to complete (as in the case of most natural resource systems), or which would be extraordinarily hazardous.

There is another valuable aspect to simulation programs -- they permit the programmer to summarize his view of the real system and transmit it to another person in a form which is far more effective than either the written or spoken word -- the material which is communicated can be used and manipulated by the second person, and thus absorbed through direct experience. This is the principal intent of the present program -- to communicate to those concerned with regulating natural pest populations, some of the structure which must be provided in making management decisions. A knowledge of the dynamics of the managed pest population, the field effectiveness of the control material, the effect of the pest on the production of host values, and the economic framework within which decisions must be made, are some of the aspects of decision making that are to be considered. It is generally true that for a variety of reasons, forest pest management is not based upon an adequate knowledge of any of these, and forest pest research is not adequately funded to produce the required knowledge. In a very real sense, the author is playing "what if?" -- he is trying to communicate to the present reader what could be done if there was sufficient knowledge available. In order to do so he has brought together a number of elementary considerations with the intention of illustrating the existence of an opportunity to elevate the standard of practice in the field.

This interactive computer program is intended to be a communications device. What is to be communicated will become clear below. At this point it is very important that the reader/user realize what is not to be communicated. The program does not produce simulations for any actual events. No result is represented as being realistic. There are several places in the text where a relationship is suggested between the results or structure of the program and certain real situations. In no such case is it being suggested that there is detailed structural agreement with the real case, nor that the program as a whole approximates any real case. In other instances, comments are made which reveal the nature of the discrepancy between this simulated program and certain known features of a real situation. In brief, whatever the merits of this program, it is not designed to obtain solutions to real problems.

Description of Program

General

The simulation contains four major elements:

(1) a simulator for the dynamics of the pest population.

(2) a relationship between pest population density and intensity of damage.

(3) a control "device".

(4) a cost-benefit analysis.

There are three population dynamics models, four damage functions, and two control procedures. Each is discussed below in detail. It is possible to choose 24 different combinations of population dynamics models, damage functions, and control procedures.

The parameters of each population dynamics model are fixed. However, some of those of the damage functions and the control devices are variable, so that the user can actually explore a very much larger number of situations than the 24 mentioned above.

The program is written in 360-Fortran IV and uses a plotting subroutine developed at the Yale Computer Center for typewriter terminal plotting. A 132 character terminal is necessary.

Population dynamics simulation

There is a choice of three different population dynamics simulators -- one which produces an oscillating density over time, and two which produce stable densities.

The oscillating model consists of the difference equation:

$$\log N_{t+1} = C_0 + C_1 \log N_t + C_2 \log N_{t-1} + C_3 \log N_{t-2}$$

where: N_j = Pest density in generation j.

C_i = Constant

This model produces an oscillation in density from about 1×10^3 to about 6×10^6. If initial conditions outside the normal population cycle are specified, transient conditions may exceed this range. The model was derived from an analysis of actual pest density data in which density in previous years affects the rate of change in density in the current generation, because there are lag effects in the system. One of these was speculated to consist of deterioration in the nutritional quality of current foliage when defoliation has occurred in previous years. Others probably consist of the normal lag in parasite, predator, and disease effects in such systems.

The model oscillates with a period of about eight years. A typical pattern is depicted in Fig. 1.[1]

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[1] Hint: The system posseses an equilibrium point at

$$\log N_e = \frac{C_0}{(1-C_1-C_2-C_3)} \quad \text{where}$$

$C_0 = +2.615$

$C_1 = +1.454$

$C_2 = -0.978$

$C_3 = -0.0173$

Figure 1.--Logarithm of pest density over time as generated by the oscillating population dynamics model.

There are two different stable models, one based upon an exponential density-dependent rate of change, and one based upon a sigmoid (logistic) model for the same process. In both cases it is assumed that:

$$N_{t+1} - R_t \cdot N_t$$
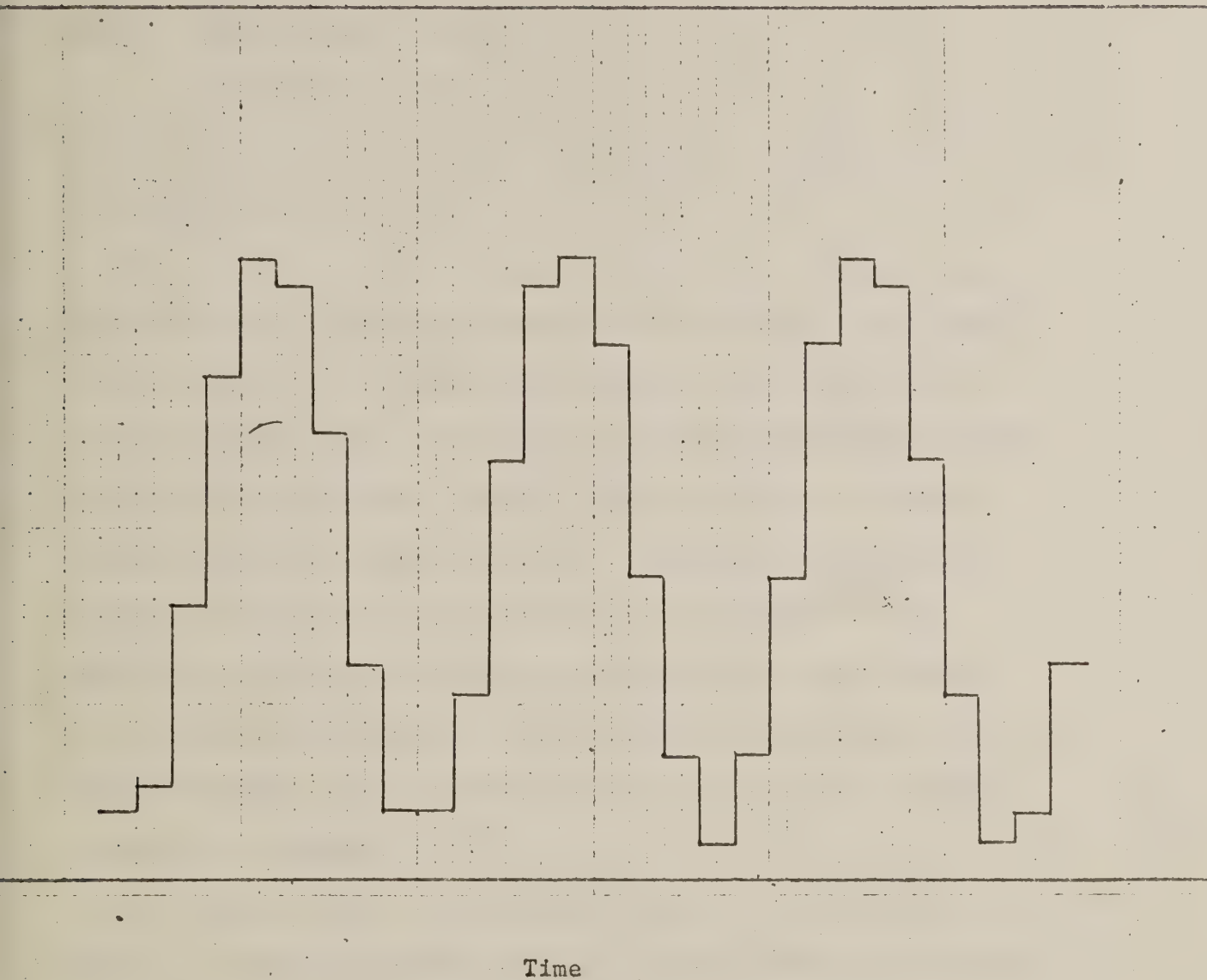
where R represents the net rate of population change in generation t.

Time

Figure 1.--Logarithm of pest density over time as generated by the oscillating
population dynamics model.

In the first case (see Fig. 2):

$$R = C_e **(-aN_t)$$

where: C = Maximum R = 2.5

a = .9163 x 10^{-5}

**designates exponentiation

These values of C and a have been chosen in order to give a stable density at 100,000. The equilibrium point in this system (where R = 1) is at $N = \ln C/a$. The time trajectory through which density moves to the equilibrium value, given an initial condition elsewhere, depends upon other properties of the relationship. However, this function has been chosen to represent a case in which R, the capacity of the pest to increase, increases (to an upper bound) as pest density is reduced. That is, a higher percentage control will be needed to maintain density at a value lower than 100,000, as density is reduced.

Figure 2.--Density dependent population change function used in the exponential population dyanmics model

$$R = Ce^{-aN_t}$$

C = 2.5

a = .9163 x 10^{-5}

Figure 2.--Density dependent population change function used in
the exponential population dynamics model

$$R = Ce^{-aN_t}$$

$$C = 2.5$$

$$a = .9163 \times 10^{-5}$$

2. Density dependent population change function used in

the exponential population dynamics model

$$R = Ce^{-aN}$$

$$C = 2.5$$

$$a = .9103 \times 10^{-5}$$

Past Density

100,000   200,000
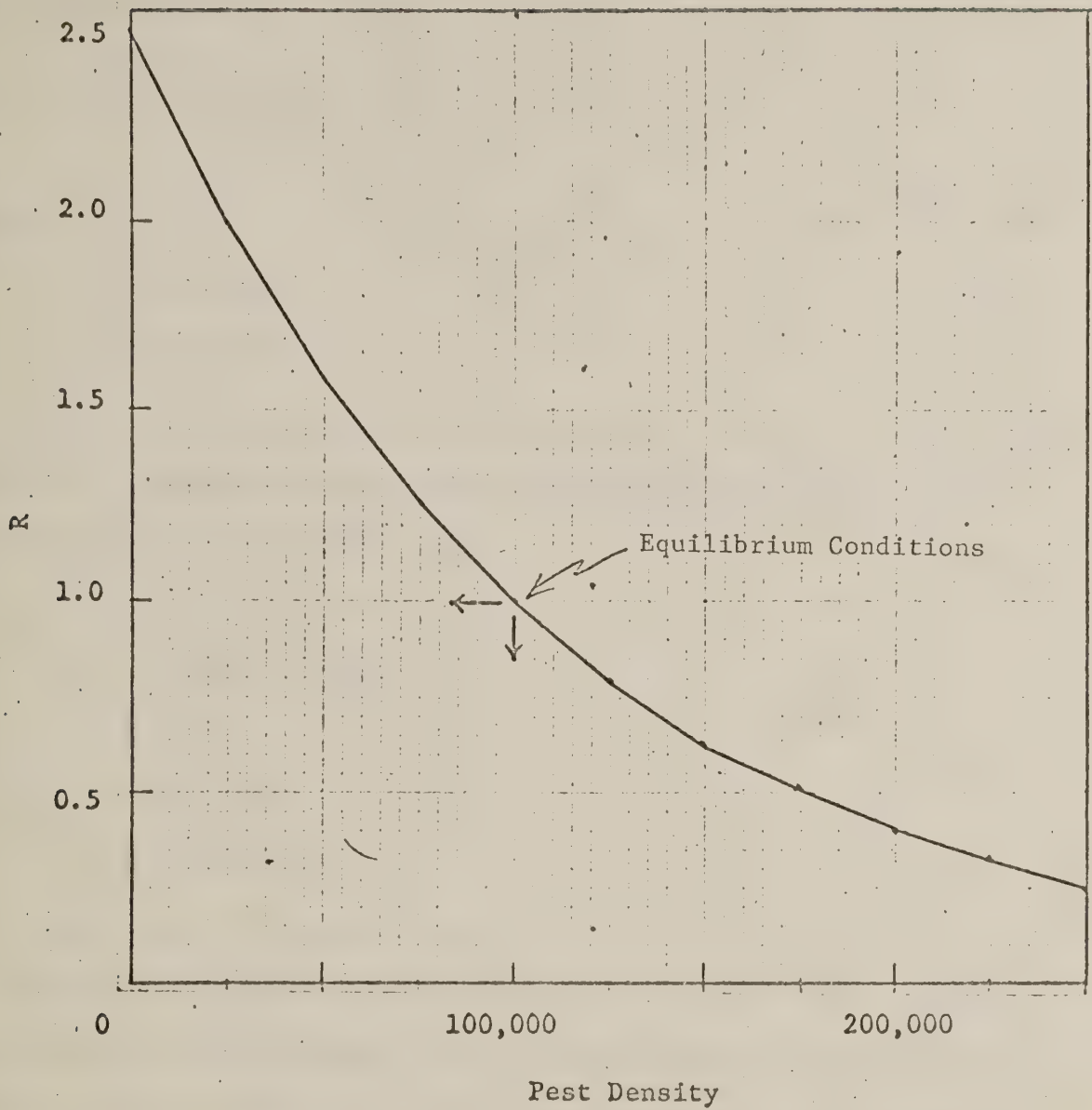
The second stable relationship (Fig. 3) is based upon the logistic function in which:

$$R = \frac{C}{1+e^{**(a+b/N_t)}}$$

where: $C = 5.0$

$a = 2.197$

$b = -81093.0$

Figure 3.--Density dependent population change function used in the logistic population dynamics model.

$$R = \frac{C}{1+e^{**(a+b/N_t)}}$$

$C = 5.0$

$a = 2.197$

$b = -81093.0$

This system again has a stable equilibrium point at N = 100,000. It differs from the previous system in that R behaves differently as density changes, and thus the same control method will be found to be optimal at a different density than in the previous system.
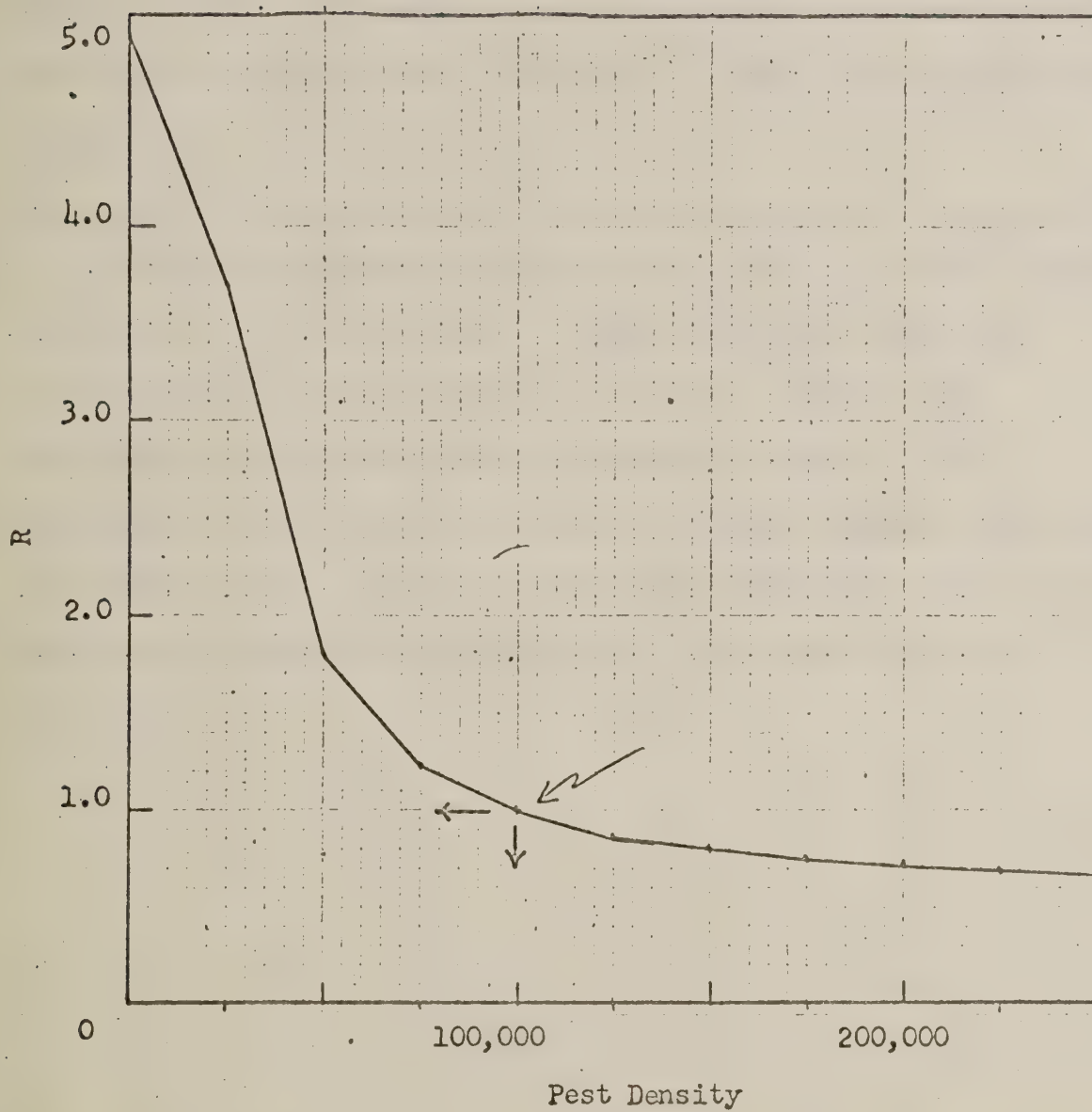
second t-table relationship (fig. 3) is based

on which:

$$R = \frac{C}{1+e^{*}(a+bN_t)}$$

$$C = 5.0$$
$$a = 2.197$$
$$b = -81065.0$$

3.--Density dependent in

population dynamics

$$R = \frac{C}{1+e^{*}(a+bN_t)}$$

$$C = 5.0$$
$$a = 2.197$$
$$b = -81065.0$$

system again has a stable equilibrium point
... from the previous space in that ... the
... changes, and thus the same control method (fig.
at a different density than in the previous system.

Figure 3.--Density dependent population change function used in the logistic population dynamics model.

$$R = \frac{C}{1 + e**(a + b/N_t)}$$

C = 5.0

a = 2.197

b = -81093.0

The time trajectories through which population density moves towards the equilibrium value for each of the two stable models are shown in Figure 4.

Figure 4.--Time trajectories of pest density (initial number = 1000) according to the exponential and logistic, stable population dynamics models.

Both of these systems approximate some general population change characteristics of real systems in that they exhibit a maximum rate of change, and an asymptotic approach to a minimal rate. The assumption that the R function depends upon density is an elementary realistic one in many cases, although somewhat controversial as a general case. In fact, the assumptions throughout this program that the relationships are deterministic, are somewhat naive and elementary.
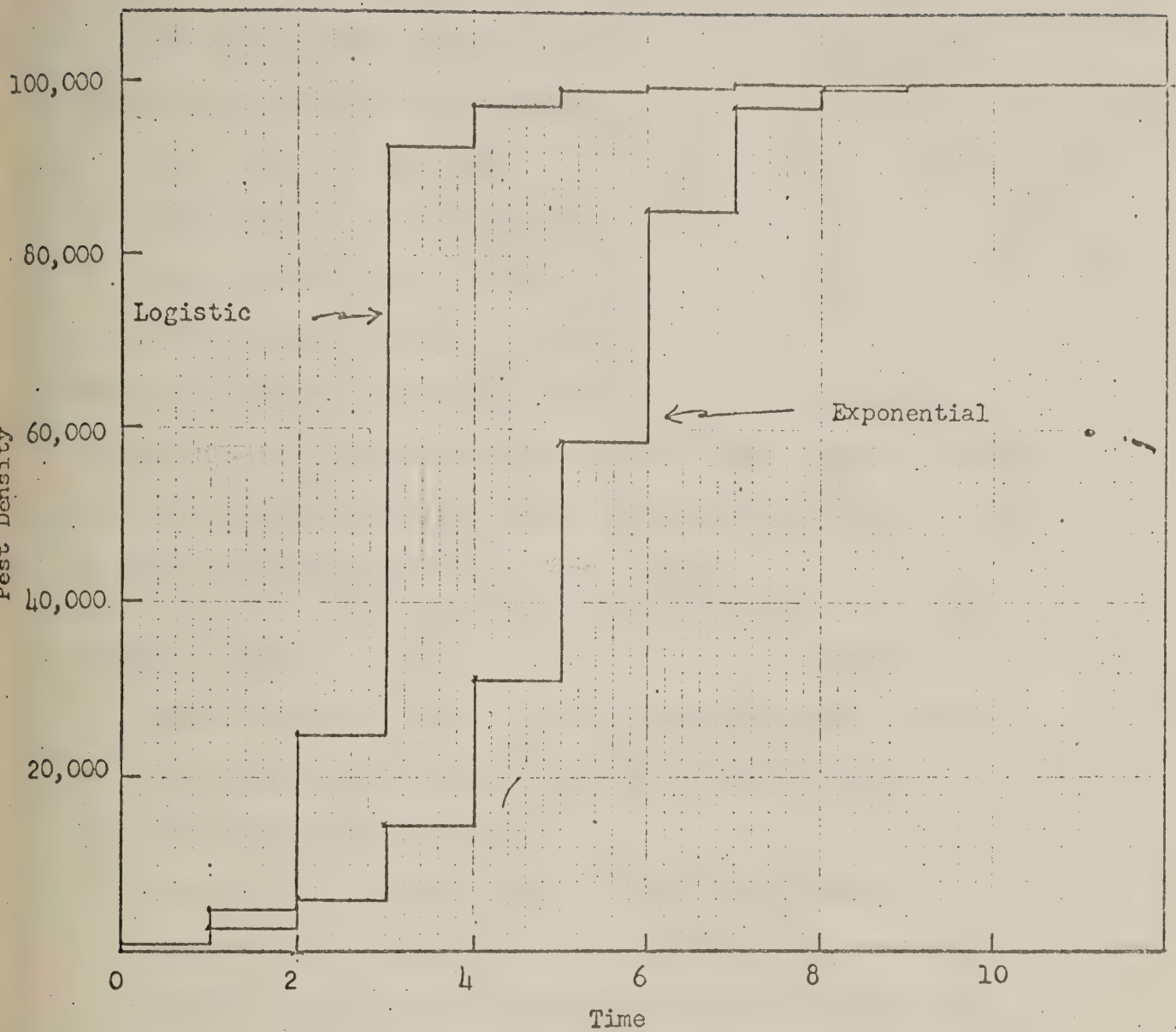
Figure 4.--Time trajectories of pest density (initial number = 1000) according to the exponential and logistic, stable population dynamics models.

Pest Density - Damage Functions

One of four different relationships between percentage host damage and pest density can be chosen:

(1) $D = 100 \ (1 - 10^{**}-aN)$

(2) $D = 100 \ (1 - 10^{**}-a \log N)$

(3) $D = 100/(1 + 10^{**}a + bN)$

(4) $D = 100/(1 + 10^{**}a + b \log N)$

Where D = percentage of complete damage, and N = pest density. (Functions 2 and 4 can be stated in simpler terms, they are presented this way to show their relationship to functions 1 and 3.) The forms of these functions are shown in Figs. 5 and 6.

Figure 5.--Damage

Damage functions 1 and 2. In each case the density at which 90 percent damage occurs is specified by the user, and the value of a calculated in the program.

Function 1: % Damage = 100. $[1 - 10^{**}(-a \text{ x density})]$

Function 2: % Damage = 100. $[1 - 10^{**}(-a \text{ x log density})]$

The pest density scale is the same as that in Figure 6 for comparative purposes.

Figure 6.--Damage functions 3 and 4. In each case the densities at which 10 percent and 90 percent damage occurs are specified by the user.

Function 3: % Damage = $100/[1 + 10^{**}(a + b \text{ x density})]$

Function 4: % Damage = $100/[1 + 10^{**}(a + b \text{ x log density})]$

The pest density scale is the same as that in Figure 5 for comparative purposes.
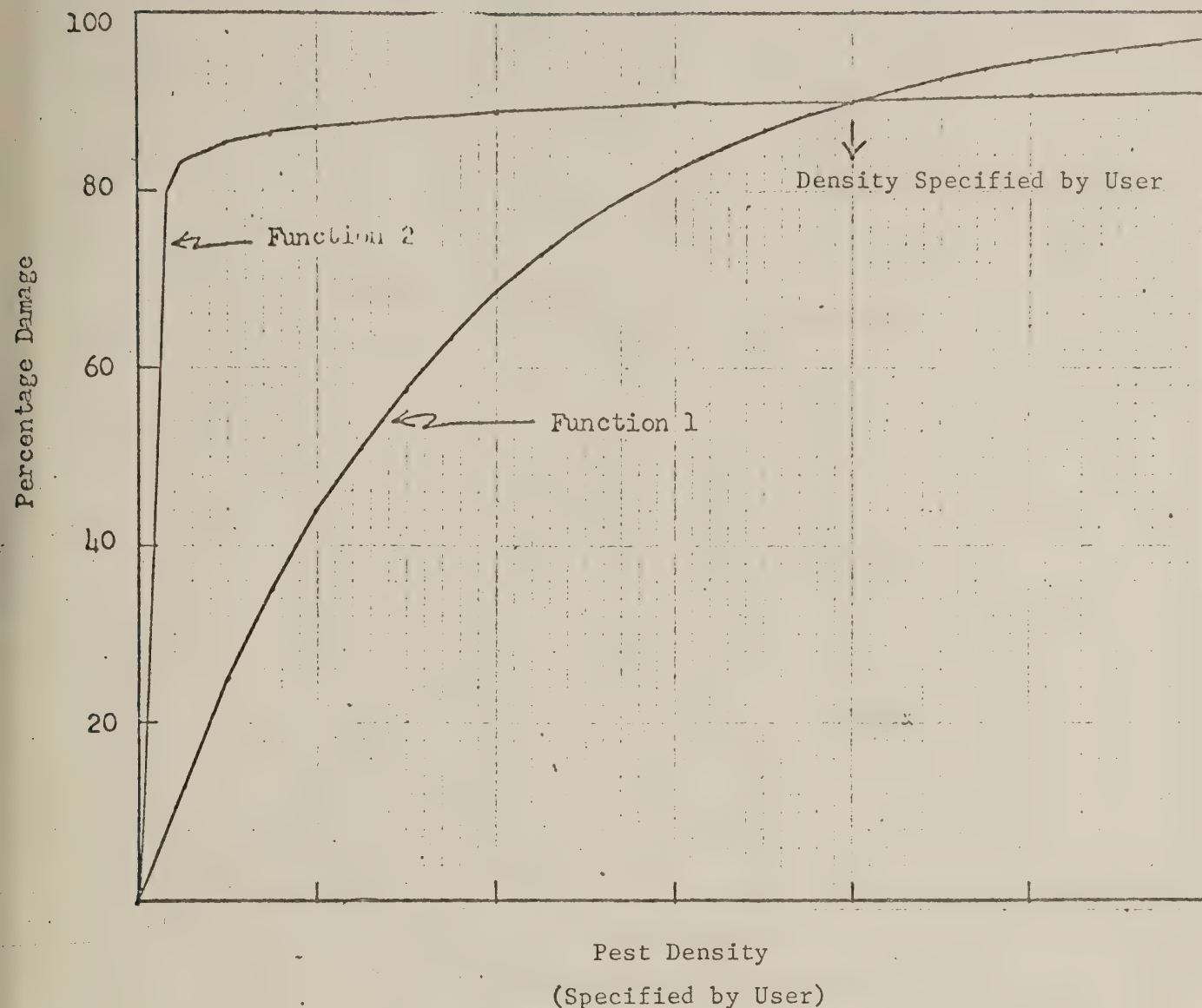
Figure 5.—Damage functions 1 and 2. In each case the density at which 90 percent damage occurs is specified by the user, and the value of a is calculated in the program.

Function 1: % Damage = $100.[1 - 10**(-ax \text{ density})]$

Function 2: % Damage = $100.[1 - 10**(-ax \log \text{ density})]$

The pest density scale is the same as that in Figure 6 for comparative purposes.
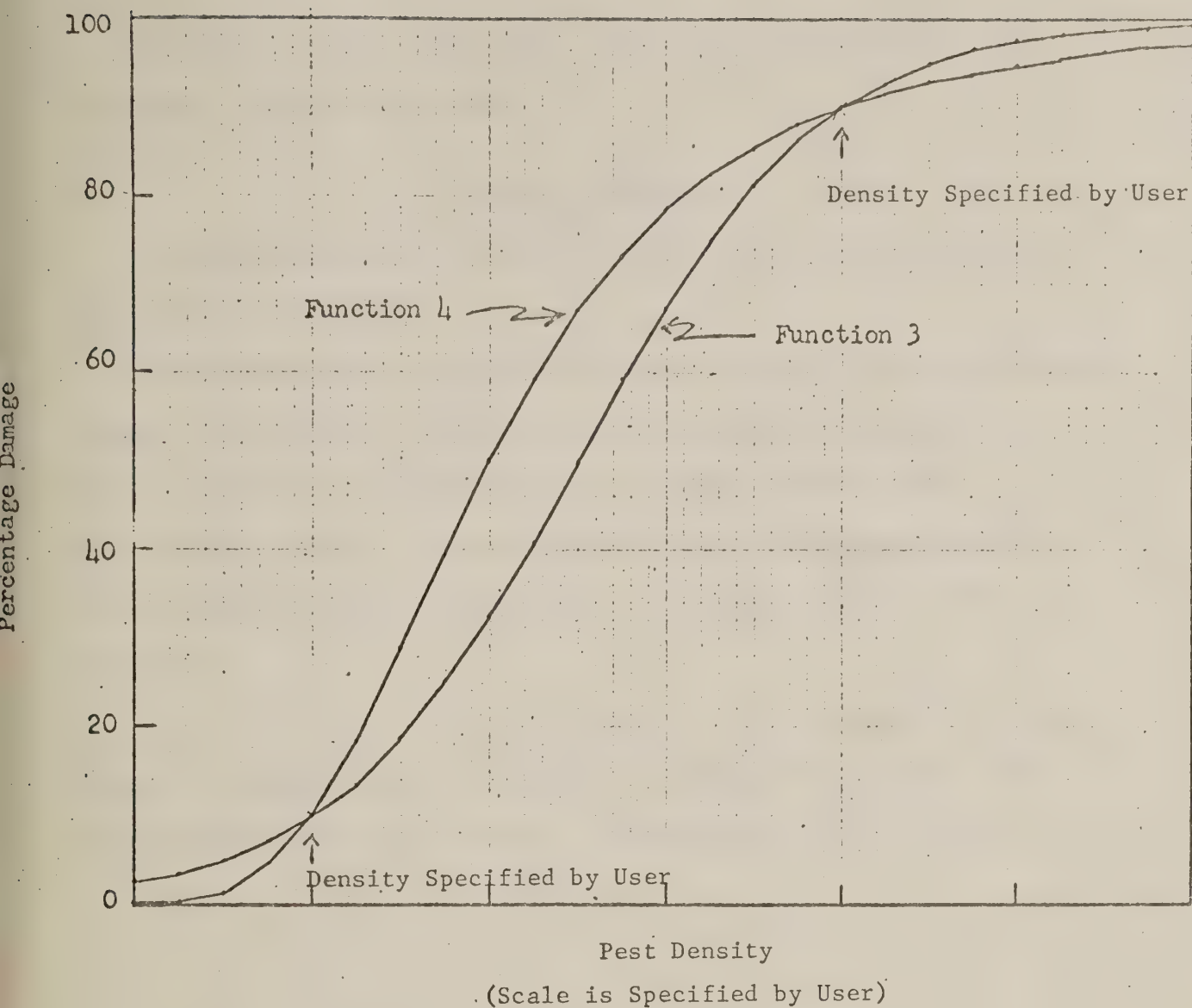
Pest Density
(Specified by User)

←—Damage Functions 1 and 2. In each case the density at which recent damage occurs is specified by the user, and the value of α is calculated in the program.

Function 1: % Damage = 100.[1 · 0*4(-α density)]

Function 2: % Damage = 100.[1 - 10**(-α× log density)]

that in Figure 6 for comparison

Pest Density

.(Scale is Specified by User)

Figure 6.---Damage functions 3 and 4. In each case the densities at which 10 percent and 90 percent damage occurs are specified by the user.

Function 3:   % Damage = 100/[1 + 10**(a + b x density)]

Function 4:   % Damage = 100/[1 + 10**(a + b x log density)]

The pest density scale is the same as that in Figure 5 for comparative purposes.

In each case, the parameters a and b are selected by the user (see below: "Using the program").

Control Procedures

Two different kinds of control are provided: an insecticide, and sterile male release.

The insecticide is assumed to possess a typical sigmoid relationship between the percentage mortality procuded, and the logarithm of dosage applied. A logistic function is used to describe the relationship (Fig. 7). Its parameters are derived from specification of the LD50 and LD95 of the material, in response to a query from the program.

Figure 7.--Dosage-response function for effect of insecticide. The curves exhibit the same LD50 of 2, and different LD95's of 10 and 20.

Percentage Mortality
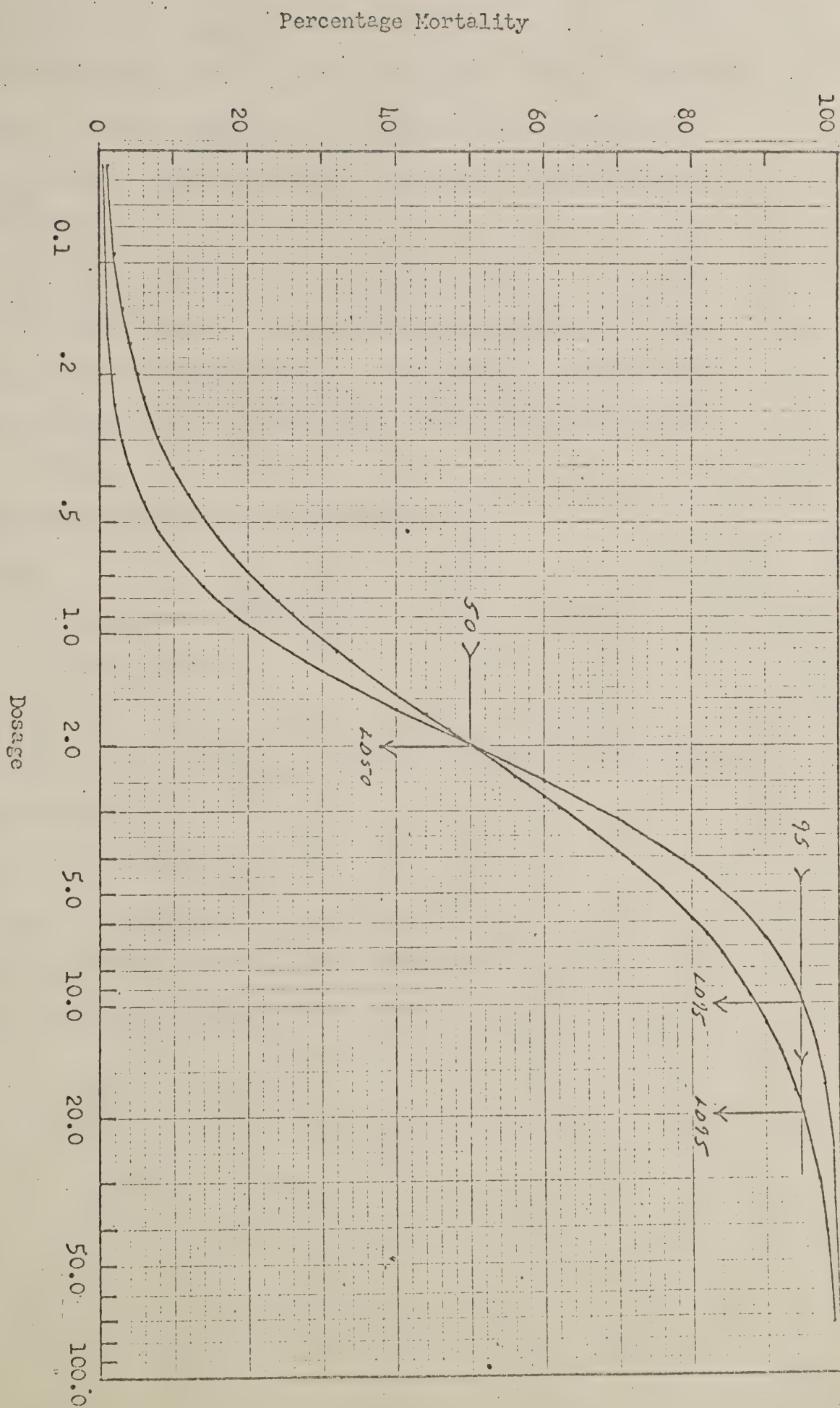
Figure 7.—Dosage-response function for effect of insecticide. The curves exhibit the same LD50 of 2, and different LD95's of 10 and 20.

The sterile-male control procedure is assumed to have an effect directly proportional to the proportion of sterile males in the male population. The male population is assumed to be one-half of the total population. A "dose-response" relationship for this approach is shown in Fig. 8.

Figure 8.--"Dosage-response" relationship for sterile male release. Percentage "mortality" obtained from given values of sterile male/ population ratios (S/D), assuming fully competitive sterile males, and a .50 sex ratio.

Percentage mortality = 100 $S/[(D/2) + S]$

where,

S = number of sterile males

D = pest density

In each case, the effects of the control procedure are assumed to be as follows:

$N_{t+1} = (1 - PM/100) N'_{t+1}$

where N_{t+1} = actual number in next generation.

N'_{t+1} = predicted number in next generation.

PM = percentage mortality from control.

control procedure is assumed to have an effect
proportional to the proportion of sterile males in the male
population. The male population is assumed to be one-half of the
... tion. A "dose-response" relationship for this approach
... n in Fig. 8.

8.--'Dosage-response' relationship for sterile male release.
... ay "mortality" obtained from given values of sterile male/
... rtor ratios (S/D), assuming fully competitive sterile males,
... 50 sex ratio.

stage mortality = $100\ S/[(D/1).+ S]$

S = number of sterile males.

D = pest density

In each case, the effects of the control procedure are assumed
follows:

$= (1 - (X)/(Y))\ N_{i,j}$

... s $N_{i,j}$ = actual number in next generation.

Y = predicted number in next generation.

= percentage mortality from control.

Figure 8.--"Dosage-response" relationship for sterile male release.
Percentage "mortality" obtained from given values of sterile
male/population ratios (S/D), assuming fully competitive sterile
males, and a .50 sex ratio.

Percentage mortality = 100 S/[(D/2) + S]

where,

S = number of sterile males

D = pest density

Figure 8.—"Dosage-response" relationship for sterile male release.

stage "mortality" obtained from given values of sterile

male/population ratios (S/P), assuming fully competitive sterile

male, and a .50 sex ratio.

—Percentage mortality = 100 S/[(P/2) + S]

Thus, no provision is made for such known effects as increased natural survival in the remainder of a generation to compensate for control-induced mortality within the generation, as a result of density-dependent survival phenomena in the system. Instead, this assumption yields the result that is usually naively expected in control operations -- a degree of reduction in pest density equal to that obtained by control.

The user is permitted to choose whether he will always apply the same level of control, or will select a unique level in each generation. In the case of sterile male control, he is permitted to specify a percentage mortality (the program then calculates dosage as the number of sterile males released), or to specify the number of sterile males to be released (the program calculates percentage mortality).

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age mortality).

Cost-Benefit Analysis

The program calculates the benefits derived from control activities on two different bases, termed short term and long term. "Short term" gains and benefits (gain minus cost) are calculated from current control costs, and the difference between the value of actual damage, and that to be expected from the current uncontrolled predicted pest population. "Long term" gains and benefits are calculated from the current control costs (as above) and the difference between the value of actual damage, and that to be expected if no control activities were ever carried out. These two calculations are needed, because, for example, certain control activities will result in higher average damage over the long term, even though they result in positive gains in the year in which they are conducted. This phenomenon can be seen most easily in the case of the oscillating model. On the other hand, certain control actions will have the opposite result -- over the long term, average damage is reduced even where there is a net loss in the year of the control activity.

In detail, cost, gains, and benefits are calculated as follows. Whenever a control action is taken, it is assumed that a fixed cost (FIX); and a variable cost, the cost per unit of the control material (VAR) multiplied by the number of units used (DOSE), are incurred. Thus,

$$COST = FIX + VAR.DOSE$$

When no control action is taken (percentage mortality = 0) no cost is incurred.

The gain in value as a result of control action (VGAIN), is calculated by subtracting the value of the percentage damage actually obtained from that expected if no control action were taken. Short term and long term gains are each calculated as described above, using the two different pest densities for calculations of expected damage.

The concept of the value of damage is purposely left very general. The user determines what value he will place upon 100 percent damage -- it can be the value of a year's growth reduction, the value of an aesthetic impact, the value of a crop destroyed, or any combination of these. Within the concept of this program, this does not matter. Something that does matter, however, is that no provision is made for the effects of damage to compound. That is, in real forest systems, one expects that in some cases severe defoliation, say, in two or three consecutive years in a decade will have a more severe impact than the same severe damage separated by years of light damage in which growth recovery takes place.

Similar remarks might be made concerning the costs of a unit

of control material. It is not intended that this should be simply

the cost of treating with say, one pound of material per acre. The

user can decide whether more general environmental costs are also to

be included.[2/] However, in this case again, no provision has been

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2/ Consideration was given to including constraints on the amount

of any toxic material used. However, while this sort of restriction

must be involved in any real case, the purposes of this program do not

require it.

---

made for say, compound effects from the accumulation of toxic material

in the environment.

Finally, no provision has been made for compounding interest on

either the costs of control or the value of gains. This would also

be required in any real analysis, as would provision for rising trends

in costs and values in an economic projection.

Using the Program

The basic program format consists of a series of inquiries from

the program concerning the values of parameters and choice of functions.

The user responds to the inquiries, and, given a complete set of input

data, the program performs the simulation and writes a report on the

results. Tables 1 to 9 contain the results of sample sessions. The

following discussion is organized around each of the inquiries.

Firstly, the program edits all input information and issues error notifications where they are appropriate. These are all self-explanatory and since it is anticipated that the user will have no difficulty responding to them, they will not be discussed in detail.

There is one general feature to be noted before proceeding with the discussion -- all inquiries which require a numerical entry, will require positive values. If a negative value is given (for example, a negative number of generations, or a negative initial density) the program will return to the beginning (the third inquiry). This permits the user to change her/his mind before entering the simulation. (Ordinarily, time-sharing systems provide for cancelling an input line before transmitting it to the system; this provision permits in addition, modification of previously entered material.) After testing for negative entries, the program also edits the input data for validity in a variety of other ways.

<u>Program Prompts and Inquiries</u>

1.   ***POPULATION REGULATION SIMULATOR***

CLEAR TABS AND SET TO 37 (RELATIVE)

The user clears all left tabs on the terminal up to 37 spaces from the left margin. This is for proper alignment in the output table when unique control rates are entered in each generation. The program will inquire:

2. O.K. ?

    After each carriage return, until the user replies "YES"
(or "Y"), permitting repetitive tries to set tabs. If they
have not yet been set, reply "NO"(or "N").

3. SELECT A POPULATION MODEL - OS, LG, EX:

    By replying "OS" the user chooses the oscillating population
dynamics model; "LG", the logistic, and "EX" the exponential.

4. SELECT A CONTROL SYSTEM - IN OR SM:

    "IN" chooses an insecticidal control system; "SM", sterile
males.

5. ENTER NUMBER OF GENERATIONS:

    Reply with the number of generations for the simulation.
This must be less than or equal to 100. A negative value returns
to the beginning of the program, "O" is an invalid entry.

6. If the insecticide control system was chosen the following prompt
will be used:

ENTER LD50 AND LD95 OF INSECTICIDE:

    These are to be viewed as field values; that is, the number
of units of the material as applied in the field necessary to
obtain 50- and 95-percent mortality, respectively. From these
figures the program calculates the parameters of the log-dose,
logistic-response function. 0 is an invalid entry, as is an
LD50 greater or equal to the LD95.

7. ENTER FIXED AND VARIABLE COST OF A UNIT OF CONTROL:

Any non-zero numbers are legal entries. Fixed cost is viewed as that cost of treatment which does not depend upon the dosage applied. Variable cost is the cost of applying a unit does (one sterile male in that case; one pound or ounce, or whatever, in the case of insecticide). The costs, in the estimate of the user, can include any relevant values. Zero is a valid entry.

8. WILL YOU APPLY UNIQUE CONTROL IN EACH GENERATION?

Reply "YES" or "NO" depending upon whether you wish to decide upon the control rate after seeing the projections in each generation ("YES"); or to specify in advance that a particular control rate will be used in all generations ("NO").

9. WILL YOU USE A CONSTANT NUMBER OF STERILE MALES?

A reply of "YES" will be followed by:

10. SPECIFY NUMBER OF STERILE MALES TO BE RELEASED EACH GEN:

Any non-negative number is valid.

A reply of "NO" (to inquiry 9) will be followed by:

11. SPECIFY PERCENT MORTALITY IN ALL GENERATIONS:

Any non-negative number is valid.

(A reply to "NO" to inquiry 9 will result in the program calculating in each generation the number of sterile males required to produce the percentage mortality specified in response to inquiry 11. A reply of "YES" will result in percentage mortality being calculated from the constant number of sterile males specified in response to inquiry 10. In each case the calculation produces results which also depend upon pest density.)

If the sterile male control system was selected and the answer
to inquiry 8 is "YES", the response will be:

12.   WILL YOU SPECIFY NUMBER OF STERILE MALES? (NOT % MORTALITY):

If the reply is "YES", the program will take the numerical
input demanded during the simulation to be the number of sterile
males released in that generation. If "NO", input will be taken
to be percentage mortality.

If the insecticidal control system was selected and the same
rate of control in each generation was specified in response to
inquiry 8 ("NO"), the next inquiry will be:

13.   SPECIFY PERCENT MORTALITY IN ALL GENERATIONS:

Any non-negative reply is valid. The program will calculate
the dosage of material required to produce this level of
mortality. Note that in the case of an insecticide, it is assumed
that this dosage is not dependent upon density. (This is a common
field assumption which has no validity. It has been shown in many
cases that it requires far more material per unit area to obtain
the same population control rate where density is low, than where
it is high. However, this program does not aim at optimizing field
application techniques).

14. SPECIFY DAMAGE FUNCTION NUMBER AND VALUE OF 100% DAMAGE:

The damage functions are numbered as presented above in the text. Function numbers 1 to 4 are valid entries. The second entry includes all relevant costs (values) associated with 100% damage to the crop.

If damage function number 1 was specified in response to inquiry 14:

15. ENTER PEST DENSITY AT WHICH 90% OF COMPLETE DAMAGE OCCURS:

Any non-negative value is valid.

If damage function number 2 was specified in response to inquiry 14:

16. ENTER LOG PEST DENSITY AT WHICH 90% OF COMPLETE DAMAGE OCCURS:

Any non-negative value is valid.

If damage function number 3 was specified in response to inquiry 14:

17. ENTER PEST DENSITIES AT WHICH 10% AND 90% OF COMPLETE DAMAGE OCCURS:

Any positive entries in which the second is greater than the first are valid.

If damage function number 4 was specified in response to inquiry 14:

BY DAMAGE FUNCTION NUMBER AND VALUE OF 100% DAMAGE:

e damage functions are numbered is presented above. In the

nction numbers 1 to 8 are valid entries. The res

ry includes all relevant costs (values) associated with th

ge to the crop.

If damage function number 1 was specified in

quiry 14:

ES1   DENSITY AT WHICH 90% OF COMPLETE DAMA

Any non-negative value is valid.

If damage function number 1 was specified in response to

14:

" LOG PEST DENSITY AT WHICH 90% OF COMPLETE DAMA

ny non-negative value is valid.

If damage function number 5 was specified in response to

nquiry 14:

MITED PEST DENSITIES AT WHICH 10% AND 90% OF COMPLETE DAMAGE

CURS:

Any positive entries in which the second is greater that the

rst are valid.

Function number 4 was specified if response to

iry 14:

18. ENTER LOGS OF PEST DENSITIES AT WHICH 10% AND 90% OF COMPLETE
    DAMAGE OCCURS:

Any positive entries in which the second is greater than
the first, are valid. Note that this restricts the range of
pest density over which damage can occur to numbers greater
than 1.

The user will find it useful to remember that pest density
in the oscillating model (OS) is not normally greater than 10^7,
except under unusual initial conditions and some control regimes.
In the case of the stable models (LG and EX), the models produce
a steady density of 100,000. The parameters of the damage
functions can be chosen to explore a wide variety of damage
rates, and consequently, gains and benefits from control, in
these population density ranges.

19.   ENTER NUMBERS IN FIRST THREE GENERATIONS:

Any positive numbers are valid. The third value is used
as the initial value in the stable model simulations, all three
are used in the oscillating case. In the latter case, it will
be useful to choose as initial values, a sequence of three from
a simulation that has run for 20-50 years, in order to examine
cases of regular oscillation rather than those with a large
transient signal effect.

If unique control was specified in response to inquiry 8
("YES") during execution the program will demand that the
control percentage, or number of sterile males, be entered
after the values of expected density and damage are written.
The inquiry

20.   consists of a ">" written under the column heading "CONTROL RATE".

Following entry of the desired control rate, the carriage
must be returned. If a negative entry is given, the program
returns to the beginning and the current simulation is aborted.

Following completion of the simulation summary, the user
is asked:

21.   GRAPHS?

A response of "YES" produces three graphs containing:
the logarithms of uncontrolled and actual pest densities over
time, the logarithms of expected and actual pest densities over
time, and uncontrolled percentage damage and actual percentage
damage over time.

Finally, the user is asked:

22.   FINISHED?

A reply of "YES" exits from the program, "NO" returns to the
beginning for another simulation.

Results

The format of the results produced by the program is illustrated
in the tables that follow.

It is intended that questions for exploration be formulated by
the user. Consequently, an extensive analysis of results is not offered
here. However, examples of the exploration of two typical questions are
shown in Table 1 - 4, and 5 - 9.

In the first case, the effects are shown of using sufficient
insecticide in the oscillating population system to produce 75, 85,
and 95 percent control in all generations (Tables 1 - 3) and the
effects of using an undisclosed control strategy on the same system
(Table 4).

...ply of ... exits from the program, and returns to the ...ing for another simulation.

...mmary of the results produced by the program is illustrated that follow.

... that questions for exploration be formulated by ...arly, an extensive analysis of results is not offered ...ymme..., examples of the exploration of the typical questions are in Table ... 1, and 5 - 9.

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Note that total short-term gains decline as increasing control
rates are applied, whereas total long-term gains increase and then decrease,
revealing that at some point between the 75 and 95 percent control rates
there is an optimum level. The results (including other simulations
on this same system) are displayed in Fig. 9. It is clear that short-
term gains are maximized between control rates of 50 and 85, if a control
strategy is used which applies equal dosages of the insecticide in all
generations. It has been shown however in Table 4 that there is some
other strategy which produces a better result than any of those used
above (it is left to the reader to discover this, or a better one --
the author would be interested in hearing about any that are better).
It would be unusual to apply at low densities when little or no damage
is expected. The usual procedure is to try to control under circumstances
which produce short-term benefits -- this is left to the user to explore.
It might be interesting to contrast the effects of controlling only at
high density with those of applying control at moderate, increasing
densities and moderate, declining densities. Although the results of
these simulations should not be taken seriously, there are some which
are worth contemplating in real systems.

Figure 9.--Short-term benefits (n) and long-term benefits (.) in a
particular simulation (see text) as control rate in the generation is
varied.

Note that short- and long-term benefits are optimized at different
control rates.
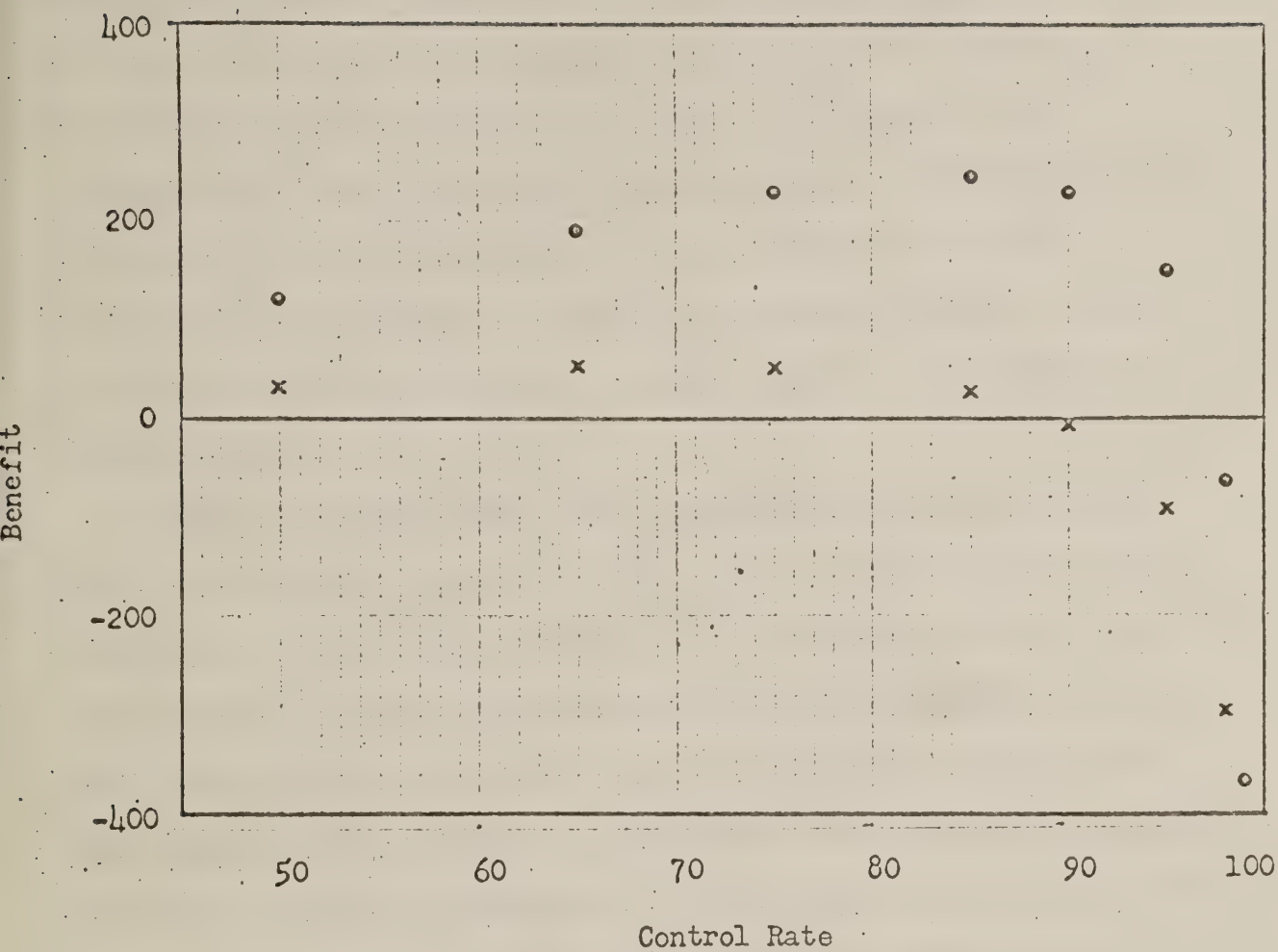
Figure 9.--Short-term benefits (x) and long-term benefits (•)
in a particular simulation (see text) as control rate in the
generation is varied.

Note that short- and long-term benefits are optimized at different
control rates.

If the user conducts other simulations on the same system, allowing the value of damage, and the pest-density damage function to vary, he will discover how important it is to have a detailed knowledge of the exact nature of the impact of the pest on the production of values in a natural resource system. The development of optimum forest pest management strategy requires a thorough integration of the results of studies in population dynamics, forest pest control, forest pest impact, and the dynamics of the production of resource values.

Tables 5 through 8 show some interesting effects of using the sterile male control procedure in the exponential population system. It is clear that the system stabilizes at a lower pest density when fewer sterile males are used than are needed for extermination of the population and that net benefits increase remarkably with the use of large numbers of sterile males. One wonders whether there is an optimal trajectory towards extermination of the population using the same total number of sterile males. Perhaps using moderate numbers when the population is high and large numbers later would be better than the same number in each generation, or perhaps the converse would be best. Table 9 shows the results of one attempt to explore this question. They reveal a typical result -- one can choose an optimal control procedure on the basis of obtaining a desired system state most rapidly, or on the basis of least net cost, and the two bases seldom provide the same result. These, however, are among topics for another discussion.

Copies of the program are available upon request from:

    Forest Insect and Disease Laboratory

    Northeastern Forest Experiment Station

    151 Sanford Street

    Hamden, Connecticut 06514

TABLE 1.

```
SELECT A POPULATION MODEL- OS,LG; EX: >os
SELECT A CONTROL SYSTEM- IM OR SM: >in
ENTER NUMBER OF GENERATIONS: >20
ENTER LD50 & LD95 OF INSECTICIDE: >.2 2
ENTER FIXED AND VARIABLE COST OF A UNIT OF CONTROL: >1 5
WILL YOU APPLY UNIQUE CONTROL IN EACH GENERATION? >n
SPECIFY PERCENT MORTALITY IN ALL GENERATIONS: >75
SPECIFY DAMAGE FUNCTION NUMBER AND VALUE OR 100% DAMAGE: >4 50
ENTER LOGS OF PEST DENSITIES AT WHICH 10%, AND 90% OF COMPLETE DAMAGE OCCURS: >5 7
SPECIFY NUMBERS IN FIRST THREE GENERATIONS: >500 1000 25000
```

| | WITHOUT CONTROL | | WITH CONTROL | | | | | | | | | VALUE OF | | |
GEN	DENSITY	DAMAGE	EXPECTED DENSITY	DAMAGE	CONTROL RATE	ACTUAL DENSITY	DAMAGE	DOSAGE	COST	SHORT TERM GAIN	BENEFIT	LONG TERM GAIN	BENEFIT	GEN
1	1068831.	51.6	1068831.	51.6	75.00	267208.	22.11	.472	3.36	14.74	11.38	14.74	11.38	1
2	10664533.	90.5	1420848.	58.3	75.00	355212.	27.14	.472	3.36	15.58	12.22	31.70	28.34	2
3	7265407.	86.9	2003384.	17.7	75.00	50000.	5.43	.472	3.36	6.15	2.79	40.73	37.37	3
4	410815.	30.0	8438.	1.0	75.00	2110.	0.28	.472	3.36	0.38	-2.98	14.84	11.48	4
5	8817.	1.1	570.	0.1	75.00	143.	0.02	.472	3.36	0.03	-3.33	-12.83	-3.35	5
6	553.	0.1	260.	0.0	75.00	65.	0.01	.472	3.36	0.01	-3.35	-13.03	-3.35	6
7	444.	0.1	1219.	0.1	75.00	305.	0.04	.472	3.36	0.06	-3.30	-3.44	3	7
8	5169.	0.7	26127.	3.2	75.00	6532.	0.82	.472	3.36	1.09	-2.27	4.00	0.72	8
9	238751.	20.3	502693.	34.2	75.00	125673.	12.14	.472	3.36	11.01	7.65	-0.00	0.72	9
10	5714212.	84.1	1799806.	63.7	75.00	449951.	31.82	.472	3.36	15.92	12.56	22.76	22.76	10
11	13054000.	92.1	604338.	38.2	75.00	151200.	14.15	.472	3.36	12.04	8.68	38.96	35.60	11
12	1810652.	63.0	33514.	3.8	75.00	8453.	1.04	.472	3.36	1.38	-1.98	31.43	28.07	12
13	43744.	4.8	1450.	0.2	75.00	363.	0.05	.472	3.36	0.07	-3.29	2.38	-0.98	13
14	1311.	0.2	255.	0.1	75.00	64.	0.01	.472	3.36	0.01	-3.35	-3.28	14
15	317.	0.0	465.	0.1	75.00	116.	0.02	.472	3.36	0.02	-3.34	-3.35	15
16	1324.	0.2	6440.	0.8	75.00	1610.	0.22	.472	3.36	0.29	-3.07	-3.36	16
17	45138.	4.9	168618.	15.5	75.00	42154.	4.65	.472	3.36	5.41	2.05	0.15	-3.21	17
18	1933100.	65.2	1470709.	59.1	75.00	367677.	27.79	.472	3.36	15.65	12.29	18.72	15.36	18
19	14094620.	92.6	1344653.	57.0	75.00	336163.	26.11	.472	3.36	15.45	12.09	29.88	18	19
20	6042759.	84.8	134142.	12.8	75.00	33535.	3.77	.472	3.36	4.53	1.16	37.14	20	20
	6244288.	774.	8794550.0	417.		2198034.0	178.	9.44	67.22	119.8	52.62	298.2	230.9	

```
YOU PRODUCED AN AVERAGE DENSITY WHICH WAS    3.52% OF THAT OF THE UNDISTURBED POPULATION,
AND  25.00% OF THAT OF THE YEAR TO YEAR CONTROLLED POPULATION.
YOU USED A TOTAL OF    9.44 UNITS OF MATERIAL AT A TOTAL COST OF    67.22
THE SUM OF YOUR SHORT TERM GAINS WAS:    119.94   FOR A NET BENEFIT OF:    52.62
THE SUM OF YOUR LONG TERM GAINS WAS:    298.17   FOR A NET BENEFIT OF:    230.95
FINISHED?>n
```

TABLE 2.

```
***POPULATION REGULATION SIMULATOR***
CLEAR TAGS AND SET TO 37 (RELATIVE)
>
OK?>y

SELECT A POPULATION MODEL- OS,LS,EX: >os
SELECT A CONTROL SYSTEM- IN OR SM: >in
ENTER NUMBER OF GENERATIONS: >20
ENTER LD50 & LD95 OF INSECTICIDE: >.2 2
ENTER FIXED AND VARIABLE COST OF A UNIT OF CONTROL: >1 5
WILL YOU APPLY UNIQUE CONTROL IN EACH GENERATION? >n
SPECIFY PERCENT MORTALITY IN ALL GENERATIONS: >85
SPECIFY DAMAGE FUNCTION NUMBER AND VALUE OF 100% DAMAGE: >4 50
ENTER LOGS OF PEST DENSITIES AT WHICH 10%, AND 90% OF COMPLETE DAMAGE OCCURS: >5 7
SPECIFY NUMBERS IN FIRST THREE GENERATIONS: >500 1000 25000
```

GEN	WITHOUT CONTROL DENSITY	DAMAGE	EXPECTED DENSITY	DAMAGE	CONTROL RATE	ACTUAL DENSITY	DAMAGE	DOSAGE	COST	SHORT TERM GAIN	SHORT TERM BENEFIT	LONG TERM GAIN	LONG TERM BENEFIT	GEN
1	1068831.	51.6	1068831.	51.6	85.00	160325.	14.85	.777	4.88	18.37	13.49	18.37	13.49	1
2	1060455.	90.5	676053.	40.2	85.00	101402.	10.12	.777	4.88	15.32	10.44	40.21	35.35	2
3	7265467.	86.9	53304.	5.8	85.00	8005.	0.00	.777	4.88	2.38	-2.50	42.96	38.07	3
4	4108815.	30.0	2016.	0.3	85.00	302.	0.04	.777	4.88	0.11	-4.77	14.96	10.08	4
5	8817.	1.1	203.	0.0	85.00	31.	0.01	.777	4.88	0.01	-4.87	0.54	-4.34	5
6	553.	0.1	197.	0.0	85.00	29.	0.00	.777	4.88	0.01	-4.87	-0.04	-4.85	6
7	444.	0.1	1769.	0.2	85.00	265.	0.04	.777	4.88	0.10	-4.78	0.01	-4.87	7
8	5160.	0.7	47495.	5.2	85.00	7120.	0.88	.777	4.88	2.14	-2.74	-0.12	-5.00	8
9	2538731.	20.3	661409.	40.3	85.00	99211.	0.93	.777	4.88	15.17	10.28	5.19	0.31	9
10	5714212.	84.1	1175246.	53.9	85.00	176376.	16.03	.777	4.88	13.91	14.03	0.31	-0.13	10
11	13054000.	92.1	1950000.	17.4	85.00	292250.	3.32	.777	4.88	7.02	2.14	34.02	20.13	11
12	1810052.	63.9	7725.	1.0	85.00	1168.	0.16	.777	4.88	0.40	-4.48	44.37	39.49	12
13	45742.	4.8	413.	0.1	85.00	62.	0.01	.777	4.88	0.02	-4.86	31.87	26.99	13
14	1311.	0.2	139.	0.0	85.00	21.	0.00	.777	4.88	0.01	-4.87	2.40	-2.48	14
15	317.	0.0	535.	0.1	85.00	80.	0.01	.777	4.88	0.09	-4.85	0.09	-4.80	15
16	1332.	0.2	11535.	1.7	85.00	1730.	0.23	.777	4.88	0.58	-4.30	-0.02	-4.87	16
17	45138.	4.4	274037.	22.5	85.00	41105.	4.54	.777	4.88	8.99	4.11	-0.20	-4.91	17
18	1933109.	65.2	1329780.	56.8	85.00	199467.	17.68	.777	4.88	19.54	14.66	23.77	18.80	18
19	1400462.0	92.6	565710.	36.7	85.00	84855.	7.68	.777	4.88	14.03	9.15	41.96	37.07	19
20	604275.	84.8	32977.	5.7	85.00	4947.	0.63	.777	4.88	1.54	-3.34	42.07	37.13	20
	6241428.	774.	6105056.0	333.		915753.31	88.2	15.5	97.65	124.7	27.06	342.9	245.2	

```
YOU PRODUCED AN AVERAGE DENSITY WHICH WAS    1.47% OF THAT OF THE UNDISTURBED POPULATION,
AND  15.00% OF THAT OF THE YEAR TO YEAR CONTROLLED POPULATION,
YOU USED A TOTAL OF    15.53 UNITS OF MATERIAL AT A TOTAL COST OF         97.65
THE SUM OF YOUR SHORT TERM GAINS WAS:     124.71 FOR A NET BENEFIT OF:    27.06
THE SUM OF YOUR LONG TERM GAINS WAS:      342.90 FOR A NET BENEFIT OF:   245.25
FINISHED?>n
```

TABLE 3.

```
SELECT A POPULATION MODEL- OS,LG,EX: >os
SELECT A CONTROL SYSTEM:-LM OR SM: >ln
ENTER NUMBER OF GENERATIONS: >20
ENTER LD50 & LD95 OF INSECTICIDE: >.2 2
ENTER FIXED AND VARIABLE COST OF A UNIT OF CONTROL: >1 5
WILL YOU APPLY UNIQUE CONTROL IN EACH GENERATION? >n
SPECIFY PERCENT MORTALITY IN ALL GENERATIONS: >95
SPECIFY DAMAGE FUNCTION NUMBER AND VALUE OF 100% DAMAGE: >4 50
ENTER LOGS OF PEST DENSITIES AT WHICH 10% AND 90% OF COMPLETE DAMAGE OCCURS: >5 7
SPECIFY NUMBERS IN FIRST THREE GENERATIONS: >500 1000 25000
```

GEN	WITHOUT CONTROL DENSITY	DAMAGE	WITH CONTROL EXPECTED DENSITY	DAMAGE	CONTROL RATE	ACTUAL DENSITY	DAMAGE	DOSAGE	COST	SHORT TERM GAIN	VALUE OF SHORT TERM BENEFIT	LONG TERM GAIN	LONG TERM BENEFIT	GEN
1	1068851.	51.6	1068851.	51.6	95.00	53442.	5.76	2.00	11.00	22.91	11.91	22.91	11.91	1
2	1000453.	90.5	1068851.	13.0	95.00	6843.	0.85	2.00	11.00	6.09	-4.91	44.84	33.84	2
3	726467.	86.9	3101.	0.4	95.00	155.	0.02	2.00	11.00	0.19	-10.81	43.44	32.44	3
4	410815.	30.0	93.	0.0	95.00	5.	0.00	2.00	11.00	0.01	-10.99	14.98	3.92	4
5	8317.	1.1	24.	0.0	95.00	1.	0.00	2.00	11.00	0.00	-11.00	0.54	-10.46	5
6	553.	0.1	108.	0.0	95.00	5.	0.00	2.00	11.00	0.01	-10.99	0.04	-10.96	6
7	444.	0.1	3341.	0.5	95.00	197.	0.03	2.00	11.00	0.24	-10.76	0.02	-10.98	7
8	5109.	0.7	171404.	15.7	95.00	8570.	1.05	2.00	11.00	7.51	-3.49	0.20	-10.80	8
9	238731.	20.3	1193302.	54.2	95.00	59665.	5.36	2.00	11.00	23.92	12.92	0.98	-11.20	9
10	5714212.	84.1	470636.	32.8	95.00	23534.	2.72	2.00	11.00	15.02	4.02	6.98	-4.02	10
11	15054900.	92.0	17090.	2.0	95.00	855.	0.12	2.00	11.00	0.95	-10.05	40.67	29.67	11
12	1810652.	63.9	331.	0.0	95.00	17.	0.00	2.00	11.00	0.02	-10.98	45.97	34.97	12
13	43742.	4.3	28.	0.0	95.00	1.	0.00	2.00	11.00	0.00	-11.00	31.95	20.95	13
14	4742.	0.2	38.	0.0	95.00	2.	0.00	2.00	11.00	0.00	-11.00	2.40	-8.60	14
15	1311.	0.2	725.	0.1	95.00	36.	0.00	2.00	11.00	0.05	-10.95	0.09	-10.91	15
16	317.	0.0	40408.	4.5	95.00	2020.	0.27	2.00	11.00	2.10	-8.90	0.31	-10.69	16
17	1324.	0.2	778735.	35.0	95.00	38937.	4.32	2.00	11.00	19.87	8.87	29.73	18.73	17
18	45138.	4.9	1070737.	51.6	95.00	53537.	5.77	2.00	11.00	22.93	11.93	46.01	35.01	18
19	1953100.	65.2	87832.	8.9	95.00	4394.	0.56	2.00	11.00	4.19	-6.81	42.38	31.38	19
20	14034620.	92.0	1011.	0.2	95.00	81.	0.01	2.00	11.00	0.10	-10.90	42.38	31.38	20
	6042759.	84.8												
	6241428.	774.	5045918.0	230.	252295.87	27.9	40.0	220.0	125.9	-94.08	373.1	153.1			

```
YOU PRODUCED AN AVERAGE DENSITY WHICH WAS    0.40% OF THAT OF THE UNDISTURBED POPULATION,
AND  5.00% OF THAT OF THE YEAR TO YEAR CONTROLLED POPULATION.
YOU USED A TOTAL OF   40.00 UNITS OF MATERIAL AT A TOTAL COST OF           220.00
THE SUM OF YOUR SHORT TERM GAINS WAS:       125.92 FOR A NET BENEFIT OF:   -94.08
THE SUM OF YOUR LONG TERM GAINS WAS:        373.05 FOR A NET BENEFIT OF:   153.05
FINISHED?>n
```

TABLE 4.

```
SELECT A POPULATION MODEL- OS,LG,EX: >os
SELECT A CONTROL SYSTEM- IN OR SN: >in
ENTER NUMBER OF GENERATIONS: >20
ENTER LD50 % LOSS OF INSECTICIDE: >.2 2
ENTER FIXED AND VARIABLE COST OF A UNIT OF CONTROL: >1.5
WILL YOU APPLY UNIQUE CONTROL IN EACH GENERATION? >y
SPECIFY DAMAGE FUNCTION NUMBER AND VALUE OF 100% DAMAGE: >4 50
ENTER LOSS OF PEST DENSITIES AT WHICH 10% AND 90% OF COMPLETE DAMAGE OCCURS: >5 7
SPECIFY NUMBERS IN FIRST THREE GENERATIONS: >500 1000 25000
```

```
****************************************************************************
6241428 6.    774.    2482911.0   197.   1355157.0   142.   1.98   12.88   27.35   14.48   315.8   302.3
****************************************************************************
```

```
YOU PRODUCED AN AVERAGE DENSITY WHICH WAS       2.17% OF THAT OF THE UNDISTURBED POPULATION,
AND    54.58% OF THAT OF THE YEAR TO YEAR CONTROLLED POPULATION.
YOU USED A TOTAL OF       1.98 UNITS OF MATERIAL AT A TOTAL COST OF
THE SUM OF YOUR SHORT TERM GAINS WAS:      27.35 FOR A NET BENEFIT OF:      12.68
THE SUM OF YOUR LONG TERM GAINS WAS:      315.79 FOR A NET BENEFIT OF:     302.92
FINISHED?>n
```

TABLE 5.

```
SELECT A POPULATION MODEL- OS,LG,EX: >ex
SELECT A CONTROL SYSTEM- IN OR SM: >sm
ENTER NUMBER OF GENERATIONS: >10
ENTER FIXED AND VARIABLE COST OF A UNIT OF CONTROL: >5 .001
WILL YOU APPLY UNIQUE CONTROL IN EACH GENERATION? >n
WILL YOU USE A CONSTANT NUMBER OF STERILE MALES? >y
SPECIFY NUMBER OF STERILE MALES TO BE RELEASED EACH GEN: >1000
SPECIFY DAMAGE FUNCTION NUMBER AND VALUE OF 100% DAMAGE: >4 500
ENTER LOGS OF PEST DENSITIES AT WHICH 10% AND 90% OF COMPLETE DAMAGE OCCURS: >3 5
SPECIFY NUMBERS IN FIRST THREE GENERATIONS: >500 500 100000
```

| | WITHOUT CONTROL | | | | WITH CONTROL | | | | | | | | VALUE OF | |
GEN	DENSITY	DAMAGE	EXPECTED DENSITY	DAMAGE	CONTROL RATE	ACTUAL DENSITY	DAMAGE	DOSAGE	COST	GAIN	SHORT TERM BENEFIT	GAIN	LONG TERM BENEFIT	GEN
1	100000.	90.0	100000.	90.0	1.96	98059.	89.83	1000.	6.00	0.86	-5.14	0.86	-5.14	1
2	100000.	90.0	99216.	90.0	1.96	97856.	89.81	1000.	6.00	0.86	-5.14	0.94	-5.06	2
3	100000.	90.0	99737.	90.0	1.96	97837.	89.81	1000.	6.00	0.86	-5.14	0.95	-5.05	3
4	100000.	90.0	99795.	90.0	1.96	97835.	89.81	1000.	6.00	0.86	-5.14	0.95	-5.05	4
5	100000.	90.0	99795.	90.0	1.96	97834.	89.81	1000.	6.00	0.86	-5.14	0.95	-5.05	5
6	100000.	90.0	99795.	90.0	1.96	97834.	89.81	1000.	6.00	0.86	-5.14	0.95	-5.05	6
7	100000.	90.0	99795.	90.0	1.96	97834.	89.81	1000.	6.00	0.86	-5.14	0.95	-5.05	7
8	100000.	90.0	99795.	90.0	1.96	97834.	89.81	1000.	6.00	0.86	-5.14	0.95	-5.05	8
9	100000.	90.0	99795.	90.0	1.96	97834.	89.81	1000.	6.00	0.86	-5.14	0.95	-5.05	9
10	100000.	90.0	99795.	90.0	1.96	97834.	89.81	1000.	6.00	0.86	-5.14	0.95	-5.05	10
	1000000.0	900.	998130.00	900.		978572.44	898.	.100E 0560.00	8.597	-51.40	9.379	-50.62		

```
YOU PRODUCED AN AVERAGE DENSITY WHICH WAS  97.86% OF THAT OF THE UNDISTURBED POPULATION,
    AND  98.04% OF THAT OF THE YEAR TO YEAR CONTROLLED POPULATION.
YOU USED A TOTAL OF  10000.00 UNITS OF MATERIAL AT A TOTAL COST OF    60.00
THE SUM OF YOUR SHORT TERM GAINS WAS:      8.60 FOR A NET BENEFIT OF:   -51.40
THE SUM OF YOUR LONG TERM GAINS WAS:       9.38 FOR A NET BENEFIT OF:   -50.62
FINISHED?>n
```

TABLE 6.

```
SELECT A POPULATION MODEL--OS,LG,EX: >ex
SELECT A CONTROL SYSTEM-- IN OR SM: >sm
ENTER NUMBER OF GENERATIONS: >10
ENTER FIXED AND VARIABLE COST OF A UNIT OF CONTROL: >5 .001
WILL YOU APPLY UNIQUE CONTROL IN EACH GENERATION? >n
WILL YOU USE A CONSTANT NUMBER OF STERILE MALES? >y
SPECIFY NUMBER OF STERILE MALES TO BE RELEASED EACH GEN: >10000
SPECIFY DAMAGE FUNCTION NUMBER AND VALUE OF 100% DAMAGE: >4 500
ENTER LOSS OF PEST DENSITIES AT WHICH 10% AND 90% OF COMPLETE DAMAGE OCCURS: >3 5
SPECIFY NUMBERS IN FIRST THREE GENERATIONS: >500 500 100000
```

	WITHOUT CONTROL		WITH CONTROL								SHORT TERM		VALUE OF LONG TERM		
GEN	DENSITY	DAMAGE	EXPECTED DENSITY	DAMAGE	CONTROL RATE	ACTUAL DENSITY	DAMAGE	DOSAGE	COST	GAIN	BENEFIT	GAIN	BENEFIT	GEN
1	100000.	90.0	100000.	90.0	16.67	83333.	88.32	.100E 05	15.00	8.39	-6.61	8.39	-6.61	1
2	100000.	90.0	97083.	89.7	17.08	80499.	87.98	.100E 05	15.00	8.63	-6.17	10.12	-4.88	2
3	100000.	90.0	96248.	89.7	17.20	79689.	87.87	.100E 05	15.00	8.96	-6.04	10.63	-4.37	3
4	100000.	90.0	95990.	89.6	17.24	79438.	87.84	.100E 05	15.00	9.00	-6.00	10.79	-4.21	4
5	100000.	90.0	95908.	89.6	17.26	79359.	87.83	.100E 05	15.00	9.02	-5.98	10.84	-4.16	5
6	100000.	90.0	95881.	89.6	17.26	79333.	87.83	.100E 05	15.00	9.02	-5.98	10.86	-4.14	6
7	100000.	90.0	95873.	89.6	17.26	79325.	87.83	.100E 05	15.00	9.02	-5.98	10.86	-4.14	7
8	100000.	90.0	95870.	89.6	17.26	79322.	87.83	.100E 05	15.00	9.02	-5.98	10.86	-4.14	8
9	100000.	90.0	95869.	89.6	17.26	79322.	87.83	.100E 05	15.00	9.02	-5.98	10.86	-4.14	9
10	100000.	90.0	95869.	89.6	17.26	79321.	87.83	.100E 05	15.00	9.02	-5.98	10.86	-4.14	10
	1000000.0	900.	964591.44	897.		798941.81	879.	.100E 06150.0	89.32	-60.68	105.1	-44.92		

```
YOU PRODUCED AN AVERAGE DENSITY WHICH WAS  79.89% OF THAT OF THE UNDISTURBED POPULATION,
AND 82.33% OF THAT OF THE YEAR TO YEAR CONTROLLED POPULATION.
YOU USED A TOTAL OF  100000.00 UNITS OF MATERIAL AT A TOTAL COST OF:       150.00
THE SUM OF YOUR SHORT TERM GAINS WAS:     89.32 FOR A NET BENEFIT OF:      -60.68
THE SUM OF YOUR LONG TERM GAINS WAS:    105.08 FOR A NET BENEFIT OF:      -44.92
FINISHED?>n
```

TABLE 7.

```
SELECT A POPULATION MODEL- OS,LG,EX: >ex
SELECT A CONTROL SYSTEM- IM OR SM: >sm
ENTER NUMBER OF GENERATIONS: >10
ENTER FIXED AND VARIABLE COST OF A UNIT OF CONTROL: >5 .001
WILL YOU APPLY UNIQUE CONTROL IN EACH GENERATION? >n
WILL YOU USE A CONSTANT NUMBER OF STERILE MALES? >y
SPECIFY NUMBER OF STERILE MALES TO BE RELEASED EACH GEN: >25000
SPECIFY DAMAGE FUNCTION NUMBER AND VALUE OF 100% DAMAGE: >4 500
ENTER LOGS OF PEST DENSITIES AT WHICH 10%, AND 90% OF COMPLETE DAMAGE OCCURS: >3 5
SPECIFY NUMBERS IN FIRST THREE GENERATIONS: >500 500 100000
```

| | WITHOUT CONTROL | | WITH CONTROL | | | | | | | SHORT TERM | VALUE OF | |
GEN	DENSITY	DAMAGE	EXPECTED DENSITY	DAMAGE	CONTROL RATE	ACTUAL DENSITY	DAMAGE	DOSAGE	COST	GAIN (SHORT TERM BENEFIT)	LONG TERM BENEFIT GAIN	GEN
1	100000.0	90.0	100000.	90.0	33.33	66667.	85.94	.250E 05	30.00	20.30	-9.70	20.30	1
2	100000.0	90.0	90481.	89.1	35.59	58277.	84.32	.250E 05	30.00	23.95	-6.05	28.42	2
3	100000.0	90.0	85414.	88.2	36.92	53276.	83.30	.250E 05	30.00	26.31	-3.69	33.50	3
4	100000.0	90.0	82213.	88.2	37.82	51122.	82.59	.250E 05	30.00	27.98	-2.02	37.04	4
5	100000.0	90.0	80004.	87.0	38.46	49234.	82.07	.250E 05	30.00	29.22	-0.78	39.65	5
6	100000.0	90.0	78594.	87.7	38.94	47806.	81.67	.250E 05	30.00	30.18	0.18	41.65	6
7	100000.0	90.0	77177.	87.5	39.32	46834.	81.36	.250E 05	30.00	30.94	0.94	43.21	7
8	100000.0	90.0	76251.	87.4	39.61	46056.	81.11	.250E 05	30.00	31.54	1.54	44.46	8
9	100000.0	90.0	75432.	87.3	39.85	45405.	80.90	.250E 05	30.00	32.04	2.04	45.48	9
10	100000.0	90.0	74879.	87.2	40.04	44898.	80.74	.250E 05	30.00	32.44	2.44	46.31	10
	1000000.0	900.	820273.87	881.		510213.87	824.	.250E 06	3000.0	284.9	-15.09	380.0	80.03

```
YOU PRODUCED AN AVERAGE DENSITY WHICH WAS  51.02% OF THAT OF THE UNDISTURBED POPULATION,
AND   62.20% OF THAT OF THE YEAR TO YEAR CONTROLLED POPULATION.
YOU USED A TOTAL OF 250000.00 UNITS OF MATERIAL AT A TOTAL COST OF    300.00
THE SUM OF YOUR SHORT TERM GAINS WAS:     284.91 FOR A NET BENEFIT OF:   -15.09
THE SUM OF YOUR LONG TERM GAINS WAS:      380.03 FOR A NET BENEFIT OF:    80.03
FINISHED?>n
```

TABLE 8.

```
SELECT A POPULATION MODEL- OS,LG,EX: >ex
SELECT A CONTROL SYSTEM- IM OR SM: >sm
ENTER NUMBER OF GENERATIONS: >10
ENTER FIXED AND VARIABLE COST OF A UNIT OF CONTROL: >5 .001
WILL YOU APPLY UNIQUE CONTROL IN EACH GENERATION? >n
WILL YOU USE A CONSTANT NUMBER OF STERILE MALES? >y
SPECIFY NUMBER OF STERILE MALES TO BE RELEASED EACH GEN: >50000
SPECIFY DAMAGE FUNCTION NUMBER AND VALUE OF 100% DAMAGE: >4 500
ENTER LOGS OF PEST DENSITIES AT WHICH 10% AND 90% OF COMPLETE DAMAGE OCCURS: >3 5
SPECIFY NUMBERS IN FIRST THREE GENERATIONS: >500 500 100000
```

	WITHOUT CONTROL		WITH CONTROL								SHORT TERM BENEFIT	VALUE OF LONG TERM BENEFIT		
GEN	DENSITY	DAMAGE	EXPECTED DENSITY	DAMAGE	CONTROL RATE	ACTUAL DENSITY	DAMAGE	DOSAGE	COST	GAIN	GAIN	GAIN	BENEFIT	GEN
1	100000.	90.0	100000.	90.0	50.00	50000.	82.29	.500E 05	55.00	38.57	-16.43	38.57	-16.43	1
2	100000.	90.0	79057.	87.8	55.85	34905.	76.73	.500E 05	55.00	55.34	0.34	66.37	11.37	2
3	100000.	90.0	63376.	85.3	61.21	24525.	70.23	.500E 05	55.00	75.57	20.57	93.84	43.84	3
4	100000.	90.0	49065.	82.0	67.03	16150.	61.24	.500E 05	55.00	103.91	48.91	143.30	88.80	4
5	100000.	90.0	34821.	76.7	74.17	9104.	47.47	.500E 05	55.00	146.06	91.06	212.54	157.54	5
6	100000.	90.0	20705.	66.7	82.35	3552.	27.13	.500E 05	55.00	197.81	142.81	314.33	259.33	6
7	100000.	90.0	8595.	46.4	92.09	680.	7.14	.500E 05	55.00	196.25	141.25	414.28	359.28	7
8	100000.	90.0	1690.	15.5	98.34	28.	0.37	.500E 05	55.00	75.63	20.63	448.17	393.17	8
9	100000.	90.0	70.	0.9	99.93	0.	0.00	.500E 05	55.00	4.36	-50.64	450.00	395.00	9
10	100000.	90.0	0.	0.0	100.00	0.	0.00	.500E 05	55.00	0.01	-54.99	450.00	395.00	10
	1000000.0	900.	357379.94	551.		138893.12	373.	.500E 06	550.00	893.5	343.5	2637.	2087.	

```
YOU PRODUCED AN AVERAGE DENSITY WHICH WAS    13.889% OF THAT OF THE UNDISTURBED POPULATION,
AND  38.86% OF THAT OF THE YEAR TO YEAR CONTROLLED POPULATION.
YOU USED A TOTAL OF  500000.00 UNITS OF MATERIAL AT A TOTAL COST OF     550.00
THE SUM OF YOUR SHORT TERM GAINS WAS:     893.52 FOR A NET BENEFIT OF:     343.52
THE SUM OF YOUR LONG TERM GAINS WAS:     2637.01 FOR A NET BENEFIT OF:    2087.01
FINISHED?>n
```
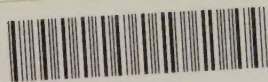
TABLE 9.

```
SELECT A POPULATION MODEL- OS,LG,EX: >ex
SELECT A CONTROL SYSTEM- IN OR SM: >sm
ENTER NUMBER OF GENERATIONS: >10
ENTER FIXED AND VARIABLE COST OF A UNIT OF CONTROL: >5 .001
WILL YOU APPLY UNIQUE CONTROL IN EACH GENERATION? >y
WILL YOU SPECIFY NUMBERS OF STERILE MALES? (NOT % MORTALITY)? >y
SPECIFY DAMAGE FUNCTION NUMBER AND VALUE OF 100% DAMAGE: >4 500
ENTER LOGS OF PEST DENSITIES AT WHICH 10% AND 90% OF COMPLETE DAMAGE OCCURS: >3 5
SPECIFY NUMBERS IN FIRST THREE GENERATIONS: >500 500 100000
```

GEN	WITHOUT CONTROL DENSITY	DAMAGE	WITH CONTROL DENSITY	DAMAGE	CONTROL RATE	ACTUAL DENSITY	DAMAGE	DOSAGE	COST	SHORT TERM GAIN	BENEFIT	VALUE OF LONG TERM GAIN	BENEFIT	GEN
1	100000.	90.0	100000.	90.0	>100000	33333.	75.93	.100E 06	105.00	70.35	-34.65	70.35	-34.65	1
2	100000.	90.0	61401.	85.0	>200000	8171.	45.20	.200E 06	205.00	198.84	-6.16	224.02	19.02	2
3	100000.	90.0	18954.	64.8	>150000	1126.	11.07	.150E 06	155.00	268.64	113.64	233.66	19.02	3
4	100000.	90.0	2787.	22.8	>30000	124.	1.49	.300E 05	35.00	106.59	71.59	407.55	407.55	4
5	100000.	90.0	309.	3.5	>10000	5.	0.07	.100E 05	15.00	17.14	2.14	449.67	434.67	5
6	100000.	90.0	12.	0.2	>5000	0.	0.00	.500E 04	10.00	0.80	-9.20	450.00	440.00	6
7	100000.	90.0	0.	0.0	>3000	0.	0.00	.300E 04	8.00	0.00	-8.00	450.00	442.00	7
8	100000.	90.0	0.	0.0	>0	0.	0.00	100.00	0.0	0.0	0.0	450.00	450.00	8
9	100000.	90.0	0.	0.0	>2000	0.	0.00	-0.0	0.0	0.0	0.0	450.00	450.00	9

```
**************************************************************************************
POPULATION EXTERMINATED
**************************************************************************************
800000.00   720.   183461.44   266.   42758.375   134.   .498E 06533.0   662.4   129.4   2931.   2388.
**************************************************************************************
```

```
YOU PRODUCED AN AVERAGE DENSITY WHICH WAS    5.34% OF THAT OF THE UNDISTURBED POPULATION,
AND  23.31% OF THAT OF THE YEAR TO YEAR CONTROLLED POPULATION.
YOU USED A TOTAL OF 498000.00 UNITS OF MATERIAL AT A TOTAL COST OF
THE SUM OF YOUR SHORT TERM GAINS WAS:        662.36 FOR A NET BENEFIT OF:    533.00    129.36
THE SUM OF YOUR LONG TERM GAINS WAS:        2931.24 FOR A NET BENEFIT OF:   2398.24
FINISHED?>n
```